RESEARCH WITH LARGE AREA IMAGING X-RAY

TELESCOPE-SOUNDING ROCKET PROGRAM

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1 Hard X-Ray Telescope

1.1 The Hard X-Ray Telescope (HXT) New Mission Concept

The work accomplished on focussing hard X-Rays in this program was the basis for a winning proposal that we submitted in response to NASA NRA 94-OSS-15, new mission concepts in astrophysics. The proposal entitled "Hard X-Ray Telescope With Simultaneous Multiwavelength Observing From UV to 1 MeV" was selected for study as a new mission concept in April 1995. The selected proposals in the area of X-ray astronomy represent three different concepts with some overlap between them. The two other concepts are high throughput spectroscopy and high resolution imaging. The preparation of the new mission concept proposal was discussed in more detail in the SR&T continuation proposal submitted last year. We were happy to learn after that, of the acceptance of the HXT mission concept proposal.

The effect of the selection of HXT as a new mission concept was to increase the relative importance of focussing hard X-rays in our SR&T program. From that point on most of the effort will be devoted to HXT related studies.

There was a period of about six months between the selection announcements and the issuing of a grant for the new mission concept studies. The SR&T grant was used in the interim to support some mission concept study work including travel for a presentation on the concept to the NASA HEMWOG and the preparation of a poster paper on the HXT mission concept that was presented at the Jan. 1996 AAS meeting in San Antonio.

1.2 Substrate Study

The preparation of the mission concept study forced us to focus upon the ultimate objective of the hard X-ray telescope, a major mission, rather than a more immediate objective, an intermediate device that would for reasons of cost and timing be more appropriate for a balloon experiment. The ultimate telescope module in our view is a replicated Wolter Type 1 highly nested telescope. In fact, the substrates are very similar to those of XMM and the number of nested cylinders per telescope module is similar for the two, 58 for XMM compared to 40 for HXT. HXT has 1/3 longer focal length and 1/3 longer substrate. The most significant difference is that HXT has 15 telescope modules compared to only three for XMM. On the other hand the diameter of the HXT substrates is only about 40% that of the XMM substrates. An entire HXT module would fit within the void at the center of an XMM module. So although HXT requires five times as many replicas than XMM from each mandrel the polished area of each mandrel is about five times smaller. So if only three replicas can be obtained before a mandrel need be repolished the total polishing effort in the two programs is quite comparable. The total mass of the optics is about the same in both cases.

During the past year, we learned from substrate investigations than the XMM electro-

forming process for producing replica mirrors cannot work in the same way for HXT. The problem is the gold layer that is used as a separation agent in replication: both electroforming and epoxy replication. The gold is deposited upon the mandrel. After separation it resides upon the reflecting surface of the replica. While gold is a satisfactory reflecting surface for X-Rays below 10 keV our measurements have shown that it is not satisfactory for higher energy X-rays.

1.3 Hard X-Ray Reflectivity: Substrate Effect

Fig 2-1 shows the 8 keV reflectivity measured at large graze angles (past the critical angle) of three substrates containing shallow uniformly spaced multilayers (Joensen et al, 1995). Uniform multilayers act like Bragg crystals. The important information is contained in the first and second order Bragg peaks at about 1.1 and 2.2 degrees. Substrate A is a polished Si wafer, B, an epoxy replica, and C a polished substrate upon which gold has been deposited prior to the multilayers. The reflectivity of the 8 kev Bragg peaks of a uniform multilayer is an indication of the hard X-ray reflectivity of the same substrates containing deep graded d-spacing multilayers. Substrate A has the highest reflectivity which is 25% at the first Bragg peak, B has 12%, and C only 1% reflectivity. Modelling indicates that the 100 keV effective area of a double conical telescope system in the geometry of the HXT mission concept made from substrate A (with a deep graded d-spacing multilayer instead of a shallow uniform multilayer) would be a few times that of substrate B with the same multilayer. Since the background is not primarily focussed diffuse X-rays but, rather, events originating near the detector, a modular telescope system made from substrate B would have to be a few times larger to equal the sensitivity of one made from substrate A.
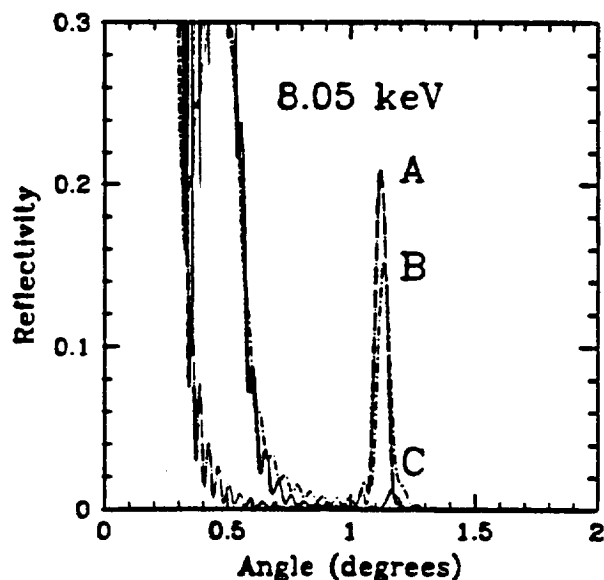

Fig. 1. Measured 8 keV reflectivity at the first Bragg peak of simple multilayers deposited on A) Si wafer, B) epoxy replica from float glass, C) gold deposited Suprasil. The peak reflectivities are 25%, 12%, and 1% respectively. These results imply much greater differences in their hard X-ray reflectivity when deposited

with deep graded d-spacing multilayers.

Atomic Force Microscopy

The reason for the differences among the A, B. C multilayer reflectors is seen when they are viewed on the finest spatial scales, 5 Angstrom sampling intervals, of an atomic force microscope(AFM). AFM images are shown in **Fig. 2-2**. Substrate A has the smoothest surface, 4 Angstroms rms, which explains why its reflectivity is best. We conclude that the greater surface roughness of the B and C substrates is due to the underlying gold layer. The crystalline nature of gold results in an rms surface roughness of about 8 Angstroms which propagates up through the stack of multilayer interfaces. Attributing the excess roughness to gold is confirmed by additional AFM upon polished substrates which have only gold deposited and gold surface electroformed replicas. The effect of the gold upon the surface roughness and its implications for poorer performance in hard X-rays is not apparent on the larger spatial scales seen in the optical Wyko interference microscope. Atomic force microscopy will be a tool for studying prototype coatings. AFM service can be obtained commercially when the needs are time sensitive and through collaboration at other times.

This finding poses a quandary. Although a gold base limits the hard X-ray reflectivity of multilayers, it is also the principal agent of separation in both electroforming and epoxy replication. Yet, with the large number of smooth, thin substrates needed for a hard X-ray telescope mission there seems to be no alternative to replication for fabrication. Therefore, we are required to develop a replication procedure that uses a non-crystalline material rather than gold as the separation agent. This is one of the major goals of the program and the quest for new separation agents will almost certainly have to continue beyond next year. Commercial replicators who have had no reason, thus far, not to utilize gold for separation have not provided any help in this endeavor. We began this past year with experimentation on a type of glassy carbon as a separator.
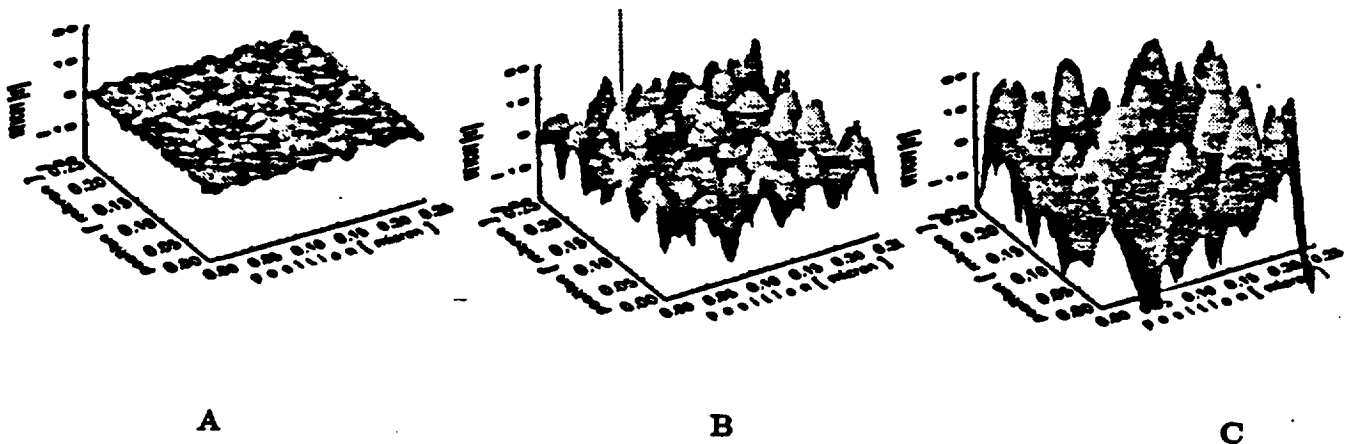

A   B   C

Fig. 2. Atomic force microscopy images of 0.25 micron region for three materials: A) uncoated "super" polished pyrex, B) an electroformed Ni substrate (a section cut from a JET-X shell), and C) gold deposited Supracil. The surface of the uncoated pyrex is much smoother than both the gold coated surfaces.

2 Multilayer Depositions

In previous years we had performed multilayer depositions at the facilities of OSMIC in Troy, MI and published the results from studies of those reflectors in papers with joint authorship. During the past year following a restructuring of their management OSMIC became less receptive to hosting us in research aspects of multilayers and more interested in their commercial business. Their deposition facilities became less available to us. Consequently, we sought other venues. Two facilities that we utilized for depositions upon gold coated substrates were a small deposition chamber at NIST and a larger one at Institut Laue-Langevin (ILL) in Grenoble. The NIST depositions were performed by their personnel under a small contract from SAO. The substrate provided to NIST was polished fused silica coated with evaporated gold. The substrates given to ILL were segments of a electroformed replica mirror shell for the JET-X experiment for Spectrum-X-Gamma, a double conical reflector. We provided the labor at ILL where the chamber was available at no cost. In addition, we purchased single layer depositions and some tri layer depositions on about 30 float glass substrates altogether in three batches from a commercial provider in our area.

We learned from our experience in searching for multilayer deposition facilities in various locales that it would be far more efficient to have a local deposition chamber under our own control, responsive to our needs. It will become increasingly important as we deal with the strong interaction between substrates and coatings. Whenever a new substrate is produced by a variation of the replication process it will have to be coated to ascertain if the process has been successful. A delay in applying a multilayer coating to a new substrate delays the next attempt at replication. Also, we wish to be sure that coatings made to the same prescription at different facilities really are equivalent. We cannot be confident of this. Consequently, we are giving high priority to establishing a multilayer facility at SAO where there will be minimum delay between replication and coating.

Both the NIST and ILL coatings were uniform multilayer depositions of about 25 NiC bilayers deposited upon the substrates discussed in 2.1.4. It is not necessary to deposit a deep graded d-spacing multilayer to verify a substrate. This method of screening substrates for deep multilayer coatings will continue to be used.

3 Replication Studies

The measurements described above showed that a multilayer deposited upon a gold coated substrate is not a good reflector. The crystalline nature of gold results in a roughness that

is propagated from layer to layer up the stack. Hence, a deep multilayer such as the graded d-spacing type that is required to function up to 100 keV loses considerable reflection efficiency if the initial substrate is gold deposited. However, gold is the most commonly used separation agent in replication of optics. Therefore, we need to find an alternative separation agent. We found that commercial replicators were not interested in solving this problem for us. Therefore, we undertook a series of experiments ourselves with flat reflectors in collaboration with Oberto Citterio of the Osservatorio Astronomico di Brera (OAB) in Merate, Italy. OAB has access to facilities for replicating optics, both electroforming and epoxy replication. SAO provided the substrates, coatings, and epoxy.

Replication experiments are performed much more conveniently upon flat substrates rather than the cylindrical integral shells of the HXT mirrors. Not only is it easier to replicate a flat than a cylinder but it is also much easier to coat it with a multilayer and evaluate the result through microscopy (atomic force and other types) and X-Ray reflection. Epoxy replication is more suitable for small flats than electroforming. It is easier to carry out, and epoxy replicas are relatively free of residual stress that exists in electroformed substrates and which results in their distortion. The separation agent can be the same for both processes. So results on separation agents and performance should apply to both forms of replication. However, epoxy replication has an additional problem. The best way to deposit multilayers is by DC magnetron sputtering which heats the substrate to 100C. This temperature is excessive for the epoxy formulations used in optics replication. Consequently we undertook a series of experiments with new formulations prepared for us by a manufacturer. We tried out several high temperature types to ascertain their viscosity, cure time, and high temperature stability. This involved performing a number of replications at the Brera Observatory with SAO provided materials. We did succeed in identifying a successful formulation that survived at 100C and had good viscosity and a relatively convenient cure cycle.

Trial separation agents with minimum crystal structure were deposited to our specifications on SAO provided float glass substrates by a commercial facility in New Hampshire. Replications were performed at OAB and evaluated back in the US by atomic force microscopy. Results on the quality of the replicated surfaces are mixed. On the one hand the replicated substrates are definitely smoother than gold but they also exhibit strange features randomly over about a quarter of the surface.

A limited uniform multilayer was deposited on two of the substrates replicated with the new epoxy. Depositions were done at the Institut Laue-Langevin in Grenoble. The performance of the multilayers was in accord with our expectations from the atomic force microscopy measurements. The reflectivity was about 20% lower than theory at all energies. The Bragg peak was present at the expected position and its strength was below theory by about 20%.

4 Wide Field Telescope

Our wide field telescope is a two dimensional lobster eye in the geometry described by Schmidt, 1975. It is a type of Kirkpatrick-Baez telescope in that it is made of two orthogonal reflector stacks of flat reflectors. In this case, the reflectors are all equally spaced perfect flats (ideally) and reflect on both sides. The two orthogonal stacks are essentially identical; the only difference being their focal length since one lies downstream from the other. In the summer of 1994 we constructed and tested a small one dimensional device in connection with a proposal to the Student Explorer Demonstration Initiative (STEDI) for a small satellite experiment. (The proposal was not selected.)

In anticipation of future small satellite opportunities we devoted a little effort this past year to experiments on improving the angular resolution by obtaining better surfaces on both faces of a reflector. A description of this is given in Section 3.4 where we also describe our plans for the coming year. This work is being reported at the 1996 SPIEE meeting (Gorenstein *et al*, 1996).

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